PUBLIC PAPER

DTPH56-13-T-000003
"INO Technologies Assessment of Leak Detection System for Hazardous Liquid Pipelines"

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FUNDING AGENCY: U. S. Department of Transportation
Pipeline and Hazardous Materials Safety Administration

Electricore, Inc. and National Optics Institute (INO), with support from TransCanada Corporation and Institut National de la Recherche Scientifique (INRS/RDDC), recently conducted research efforts on the development of a transportable leak detection system demonstrating the ability to externally locate, identify, and assess small liquid and gaseous leaks (weepers/seepers) from a safe standoff distance. The project team focused its assessment on the following three approaches: 1) ultraviolet (UV) Raman LIDAR, 2) infrared (IR) differential absorption LIDAR (DiAL), and 3) UV fluorescence LIDAR (LIF); a fourth option, UV-DiAL, also underwent limited analysis and testing. At present, INO has progressed to demonstration of these technologies under realistic conditions. The team concluded that for this application, either UV or IR absorption techniques are preferred; however, further iterative field trials will be required to determine the most adequate approach.

Background

Pipeline operators cannot easily and efficiently detect small leaks over extended lengths of pipeline. Some pipelines have distributed sensors that relay measurements to a software that raises an alarm when changes in the measurements indicate a leak. Unfortunately, these systems cannot detect leaks smaller than approximately 1% of the total flow, which is a significant loss: weepers/seepers thus go undetected. Specialized leak detection systems such as vapor permeable sensor tubes, optical fiber sensor networks, or electrical sensor cables fitted along the pipeline are hugely expensive on a per-mile basis and are only installed over environmentally sensitive terrain.

If weepers/seepers are to be detected over the entire length of pipeline, it must be through other means. The best and most feasible weeper/seeper detection system is a standoff, mobile sensor that regularly surveys the pipeline from the ground or air. The response time is not as quick as those for larger leaks, but is significantly cheaper than the aforementioned specialized approaches.

Small leaks could indicate the imminence of much larger leaks and their detection will reduce such consequences as: loss of life, loss of product, prolonged down time, irreversible environmental damage, remediation, legal, manpower, and security. Even though the survey period is long, detecting the leaks at early stages allows for a better management of risks and consequences. The platforms that INO is developing are based on principles put forward by most remote leak detection specialists. INO is striving to bring the platforms to a technological level which renders the standoff monitoring at an acceptable price point, both at the purchase level and at the maintenance/operations level.

All previous optical remote leak detection concepts relied on some form of infrared spectroscopy, active (with lasers) or passive, all of them having been originally demonstrated on natural gas pipelines. In particular, the classical two wavelength differential absorption LiDAR in the IR has been demonstrated to be able to detect leaks of liquid petroleum products in very controlled conditions, unlike real world right of ways. The working concepts of INO's platforms differ from these previous remote optical leak detection systems either by the approach (resonant UV fluorescence of BTEX compounds or UV Raman of the volatile hydrocarbons in the vapor plume) or by the principle of operation (broadband or multi-wavelength IR absorption).

Regardless of the approach, pipeline operator TransCanada Corporation informed the team that a successful optical remote leak detection system would need to detect as well as a pig with an acoustic leak detection system: 0.1 L/min (around 1 barrel per day). It would need to be airborne and be able to generate data every 250 milliseconds in order to be able to accurately map the right of way of hazardous liquid pipelines.

Project Approach

In the absence of a usable model for the formation of a vapor plume above a liquid petroleum product leak (in almost every case, a buried leak), a simplified model of a liquid filled pan at the ground surface was used.

All approaches relied on the presence of a vapor plume of alkanes and aromatics over the leak area as they are the main components of petroleum products. Pentane, being the most abundant and having the highest vapor pressure of the liquid alkanes, was used for limit of detection (LOD) evaluation of the IR-DiAL and UV-Raman. Benzene was used for UV-LIF and UV-DiAL limit of detection evaluation.

To determine the feasibility of each approach, the following parameters were used:

- Airborne platform (fixed wing or helicopter)
- Flight height: 50 m
- Flight speed: 150 km/hr
- Flight trajectory: Along the pipeline ROW, slightly to the side (~ 5 m from center)
- Flight length: hundreds of miles (hours of data)
- Lateral field of view: All of ROW (20-30 m)
- Simultaneous positioning by GPS and IMU
- Frequency of inspection for oil pipeline: every two weeks
- Data product: leak zone size and geographical position
- Smallest detectable leak: 0.1L/min (ideal)
- Spatial resolution/detection accuracy: 10 m
- Time from survey to delivery of data products: 12 hours.
- Cost: $25-$30/km of pipeline + cost of aerial platform
- Measurement time: 250 milliseconds

Feasibility Study Results

UV-Raman

All alkanes and aromatics present in crude oil have a Raman peak in the vicinity of 3000 cm^{-1}. If the optical measurement integrates the Raman returns in a sufficiently large spectral band, all the hydrocarbons contribute to the signal. Raman LIDARs do not depend on a reflection from the ground and are independent from excitation wavelength. The major drawback is the very small Raman cross-sections. In order to have a measurable signal in 250 milliseconds, the laser at 355 nm needs to be relatively high power. The laboratory testing confirmed the initial modeling and it is feasible to detect small weeper/seeper leaks using a 355 nm Raman LiDAR at a distance of 50 m and flying at 80 knots. UV Raman was preliminarily chosen to be the most feasible method and underwent intermediate scale testing.

IR-DiAL

It was confirmed that optical absorption from alkanes would be significant, but the strength of the return signal depends on the reflectivity of the ground. Unfortunately, alkanes have a very broadband spectral signature in the 3.4 to 3.6 µm range. This spectral signature could be difficult to distinguish from that of the ground's spectral reflectivity and adversely affects the limit of detection. Wet ground is almost spectrally flat, but has a low reflectivity. Dry ground has much higher reflectivity but a complex signature, and vegetation is somewhere in between. LOD is variable and it is a challenge to give a unique number. In spite of this drawback, it is feasible to detect small weeper/seeper leaks using broadband IR absorption LIDAR with return from the ground. However, the team decided to focus on UV-Raman for the next phase of testing.

UV-LIF

In contrast with the other two platforms, the UV-LIF platform's feasibility was done using benzene. Benzene has useable absorption and fluorescence peaks in the deep UV, between 225 and 270 nm. Although it would be possible to study the feasibility of optical absorption as a means of detecting leaks, INO proposed the use of fluorescence, practically the same hardware being used in both cases. The expected concentration of benzene is much lower than that of alkanes, and it was shown that at atmospheric pressure, in nitrogen, there is very strong quenching of the fluorescence; an unexpected result. It would be close to impossible to detect small weeper/seeper leaks using a fluorescence LIDAR, and no further testing was conducted.

Initial Testing

UV-Raman

The Raman platform was modified so that the optical measurement covers the Raman returns over a sufficiently large spectral band for all the hydrocarbons to contribute to the signal. For the different iterations of modifications, the Raman signal was measured over a 650 cm^{-1} interval. Raman LIDARs do not depend on a reflection from the ground but ground fluorescence is an interfering process. The major modifications were thus on the optical filtering unit, the optical detectors and the detection electronics. The aim of the modifications was for a simplified system with an enhanced limit of detection. The simplified system would cost less to manufacture and maintain.

Testing done outdoors showed that there was still an important contribution from ambient light reflecting on the background. This indicates that the final platform would need to be further enhanced by using gating on the detectors, smaller optical detection bandwidth and smaller detection footprints on the ground; these modifications were not possible within the timeframe of the project. In order to measure a LOD from which scaling could be performed, INO used a black non-reflecting background for measurements. Test performed on concentrations of about 3000 - 4000 ppm-m for pentane, 1500 – 2000 ppm-m for gasoline and 100 ppm-m for diesel in the outdoors suggested a LOD of the system below 1500 ppm-m for all hydrocarbons, which was the target for the modified system.

Intermediate Scale Testing

The intermediate scale tests were performed at Institut National de la Recherche Scientifique (INRS) where an underground leak was simulated into a large sand container. Simulation of airborne measurements was achieved from a ground based installation thanks to a tilted mirror mounted 5 meters over the contaminated soil top layer. Analysis of the air composition above soil and under the soil surface during the whole experiment duration with a commercial PID/FID instrument allowed for the monitoring of hydrocarbon concentration at various locations in the simulator. These are used as reference measurements to correlate with the UV-Raman / IR absorption data.

Analysis of these reference measurements showed a major concern as to the validity of the original vapor plume model. There is a strong vertical concentration gradient with the highest concentration very close to the ground; as a result, it has an impact on the minimum detectable leak size. It also has an impact on the eventual design of an optimized measurement hardware. Moreover, the use of a tent to enclose the vapor plume probably reduced the gradients with respect to real-world conditions, with drafts and wind. Pipeline operators' interest is to measure a leak of a given size; however, the leak detection systems proposed here measure concentration of hydrocarbons in the vapor phase around a leak. And as the intermediate scale testing showed, it is a challenge to correlate a measured concentration to an actual leak size. To elaborate a standardized testing procedure for leak detection systems would be beneficial for the industry as it would allow comparing performances of different systems.

UV-Raman

Tests confirmed the importance of using gating on the detectors and smaller optical detection bandwidth. The problem is that a large number of the molecules to be detected are very close to the ground. The hardware, as built, could not resolve the portion just above ground where the concentration is maximum. It is recommended to go with a transient digitizer and a laser with a shorter pulse length (<1 ns) or a fast gateable detector used with a current integrator. In addition, a high pulse energy, high power (10 W) laser is needed. Due to additional cost of proposed hardware and weak concentration encountered over the simulated leak, INO suggested abandoning this technique.

Because of the work done in this phase, the assumption that using Raman scattering would have the best sensitivity was revisited. Raman still has the advantage of being scalable with laser power, unlike absorption techniques; however, using high power UV lasers has its own set of problems. INO decided to assess both IR-DiAL and UV-DiAL techniques in further testing.

IR-DiAL

Intermediate scale tests confirmed the sensitivity of the approach. Moreover, this approach does allow measurement of the very high concentration of hydrocarbons encountered next to the soil surface. An important effort was then placed on ground variation study combined with different measurement strategies. The results showed that it is not possible to ascertain that the measured signal is due to absorption by hydrocarbons when the concentration obtained is below 250 ppm-m of actual molecules. When the measured concentration is higher than 250 ppm-m, it is indicative of the very probable presence of alkanes. In light of this, IR LiDAR should be revisited as a viable approach to leak detection for a leak generating a vapor concentration higher than 250 ppm-m.

UV-DiAL

Open-cell tests determined a limit of detection of benzene around 1.5 to 2.5 ppm-m of benzene molecules. Although its principle is similar to IR absorption, it should not be affected by the ground reflectivity because of the very small difference in wavelength between ON and OFF absorption wavelengths. However, benzene represents only a small and variable fraction of the overall composition of petroleum products and this is estimated to represent an LOD of about 100 ppm-m in alkane equivalent. In light of this, UV-DiAL of benzene would be the most sensitive approach, even though the effective LODs of the different techniques are all in the same range.

<u>Conclusions</u>

The techniques assessed under this program are very close in LOD when looking at vapor plume detection. Other requirements such as cost, mass, size, power, false alarms, ease of use need to be considered. Moreover, the right technique might differ from pipeline to pipeline, depending on vapor migration through the ground, soil temperature, soil cover, and other factors. Leak detection through a generated vapor plume will work best in warm climates. As in many instances, only field trials will determine the most adequate approach. Follow-on work could focus on looking at better ways of detecting through absorption in the UV; there could be ways to simplify the approach by not using costly stabilized laser systems. INO is looking into promising alternatives and is seeking the opportunity to participate in field trials, on simulated leaks or real pipelines.

In the course of this project, it was determined that the vapor concentration is not significant over an underground leak and there is a strong concentration gradient over the soil surface; the most concentrated fraction being in the first few centimeters over the surface. To ensure a maximum of sensitivity, the chosen technique should be able to collect signal from all of the probing path. This gives a serious advantage to absorption techniques. Although UV-DiAL looks promising, the technique has not been studied in depth within this project. Having a better idea of the vapor behavior over a leak, it is recommended to complete a new pros and cons exercise considering only the two absorption techniques.

INO's recommendations would be for further simulated tests and studies but for absorption measurements only. For IR absorption, the uncertainty lies in the expected changes in soil reflectivity along the various ROWs. Validation of INO's LOD estimates is therefore proposed as fllow-on work. Experimental measurements of ground reflectivity over pipeline right-of-ways are proposed. For the UV absorption technique, tests and optimization are proposed. The data analysis algorithm needs to be refined and independence from soil reflectivity changes is to be demonstrated. At this point, measurements done over a a small number of soil types may be sufficient. Design alternatives need to be assessed in order to reduce size, cost and complexity of the present design. INO sees an optimized UV absorption based weeper/seeper leak detection system in the very near future.

Acknowledgments

This work was funded by the U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA), Contract # DTPH56-13-T-000003. For further information, please visit the following link:

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